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Can Wing Tip Vortices Be Accurately Simulated?

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14. ABSTRACT
Modeling and Simulation (M&S) computational fluid dynamics (CFD) techniques were used to better understand wing tip vortices about a wing section. The CFD results were compared to experimental wind tunnel data derived from the University of Iowa (Ref. 2). The experiment used Stereoscopic Particle Image Velocimetry (SPIV) to measure the flow field. The SPIV data from the experiment illustrates the vortex core development and behavior downstream of the trailing edge of the wing section. Three CFD simulations using various mesh sizes and time steps were completed and compared to the experimental results. Two dimensional plots of modeled local flow field velocity over freestream velocity were visualized using *VisIt*. *VisIt* is used to graphically represent the numerical results of the simulations. Once the M&S results were visualized, the approximate vortex core size and position were measured and compared to the experimental data. The results show that the larger meshes closer approximate the experimental data. Further refinement of the mesh sizes in future simulations are expected to improve the approximate numerical solutions from the simulations, which would allow for more accurate predictions of vortex formation and behavior.

15. SUBJECT TERMS
Computational Fluid Dynamics, Wind Tunnel, Vortex, Stereoscopic Particle Image Velocimetry (SPIV), Wing, VisIt, Unstructured Grid, Modeling & Simulation, Aerodynamics, Flow Visualization, Numerical Investigation, Aero Suite

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Modeling and Simulation (M&S) computational fluid dynamics (CFD) techniques were used to better understand wing tip vortices about a wing section. The CFD results were compared to experimental wind tunnel data derived from the University of Iowa (Ref. 2). The experiment used Stereoscopic Particle Image Velocimetry (SPIV) to measure the flow field. The SPIV data from the experiment illustrates the vortex core development and behavior downstream of the trailing edge of the wing section. Three CFD simulations using various mesh sizes and time steps were completed and compared to the experimental results. Two dimensional plots of modeled local flow field velocity over freestream velocity were visualized using *VisIt*. *VisIt* is used to graphically represent the numerical results of the simulations. Once the M&S results were visualized, the approximate vortex core size and position were measured and compared to the experimental data. The results show that the larger meshes closer approximate the experimental data. Further refinement of the mesh sizes in future simulations are expected to improve the approximate numerical solutions from the simulations, which would allow for more accurate predictions of vortex formation and behavior.

Can Wing Tip Vortices Be Accurately Simulated?

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[a]Science and Teacher Researcher (STAR) Program, Cal Poly San Luis Obispo
[b]Air Force Flight Test Center, Edwards Air Force Base, CA

Wingtip Vortices and the Rationale of This Project

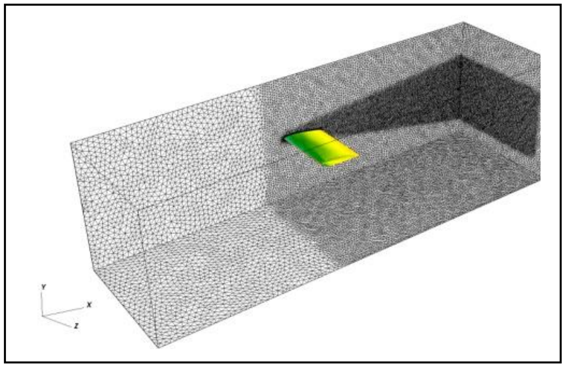
Wingtip vortices are the result of a pressure difference between the top and bottom of an aircraft wing or helicopter rotor moving through air. In military applications, wing tip vortices have adverse effects on towed vehicles and cause additional tail buffeting.[2] In commercial applications, winglets have been installed on passenger aircraft to minimize vortex formation and reduce lift-induced drag.[2]

Visually, wingtip vortices can be thought of as a horizontal tornado (as shown in Figure 1), whose cross-sectional area increases with increasing downstream distance.

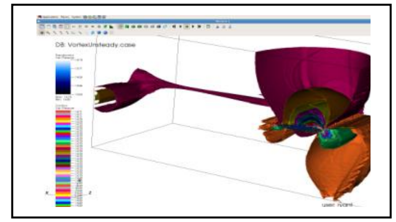
Figure 1 – Visual Representation of Wingtip Vortices

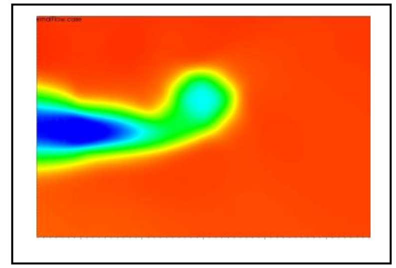
From a computational standpoint, modeling wingtip vortices has been a challenging area of study. It has only been in recent years that computational tools that better resolve and approximate wingtip vortices have been developed. This project sought to expand on gains made by using incrementally more computationally intensive simulations. Determination of the accuracy of the model wingtip vortices was accomplished by comparing simulation results to experimental data.

Methods



Numerical results of simulations sent to visualization program *VisIt*





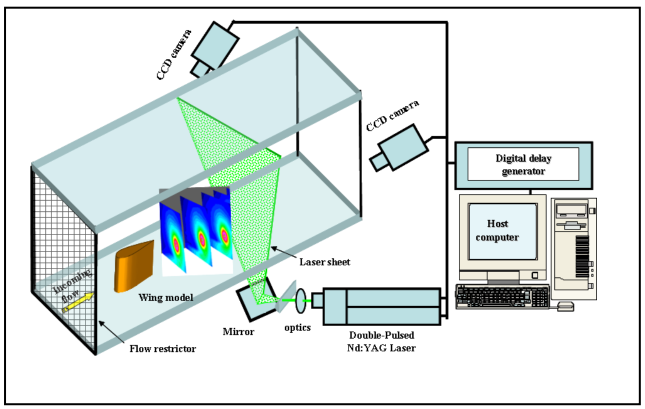
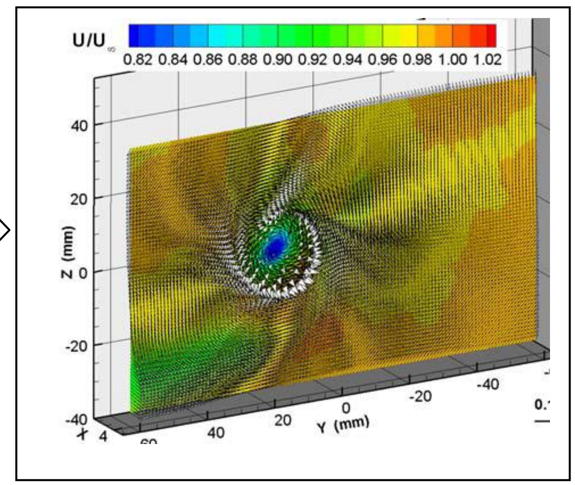
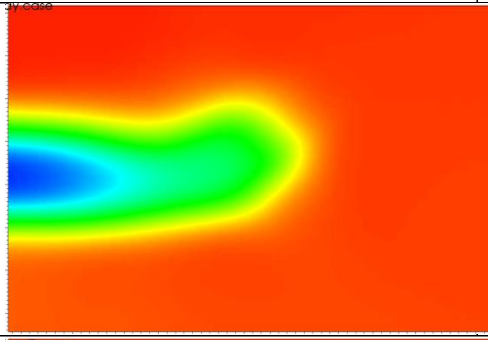
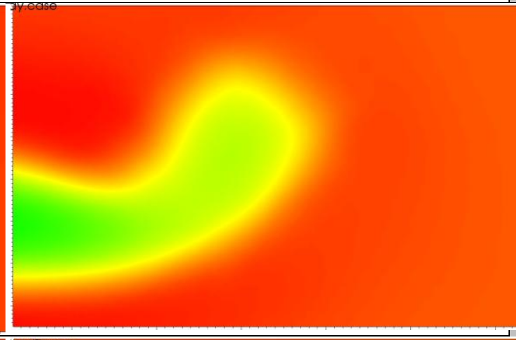
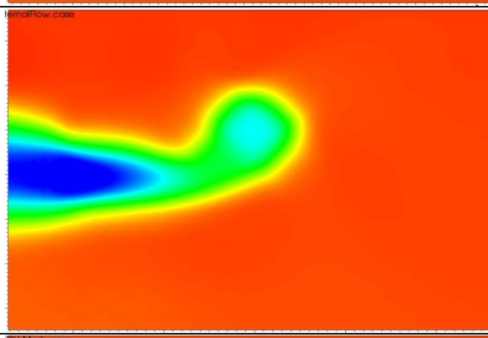
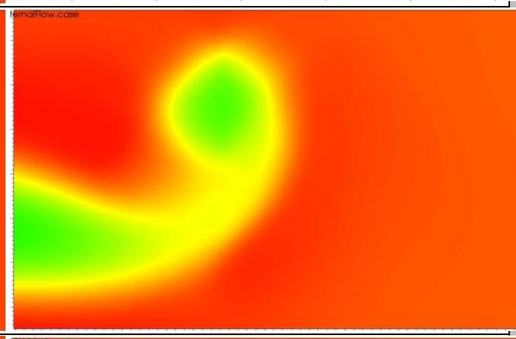
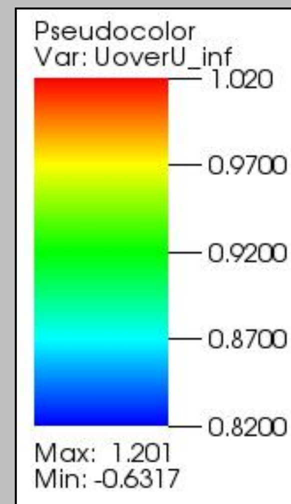
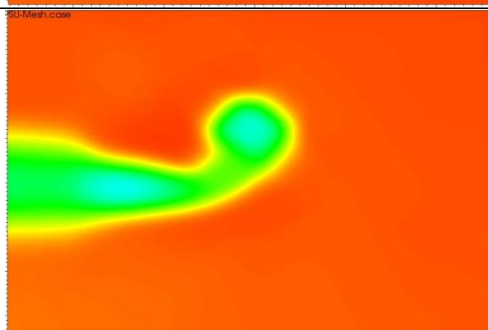
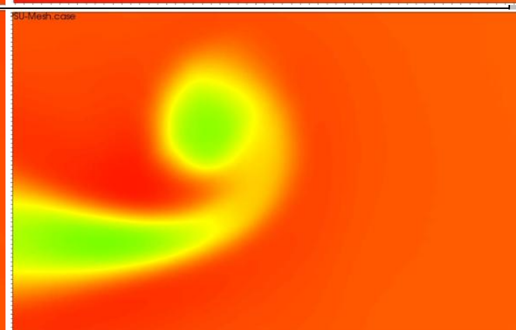
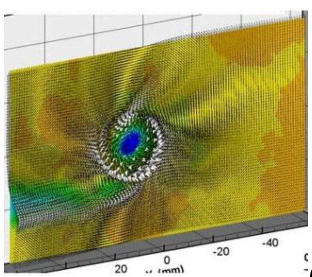
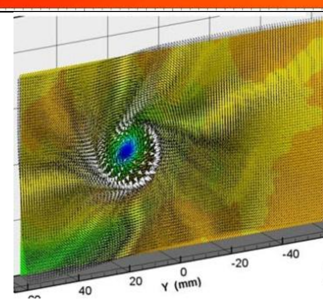


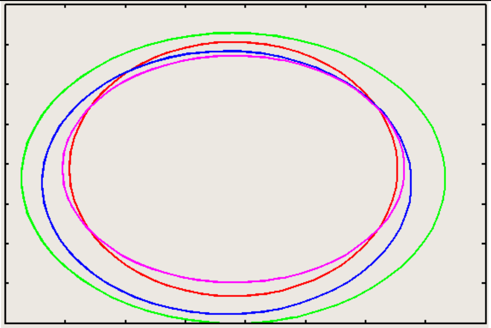
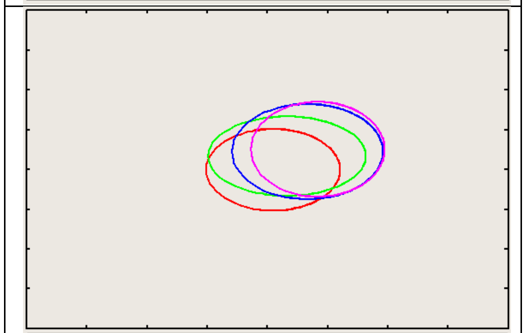
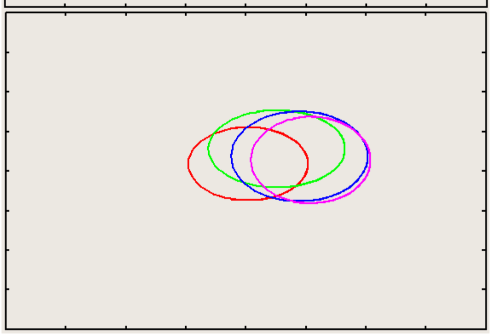
Figure 2 – Experimental Setup using StereoScopic Particle Image Velocimetry (SPIV) (Ref 2)

Data from Iowa State University wind tunnel experiment compared to simulation.



Ref 2

Plots of Instantaneous Velocity over Freestream Velocity and Equivalent SPIV Images			
Simulation	4″ downstream of trailing edge	16″ downstream of trailing edge	**Legends**
Sim0			*Simulation*
Sim3			
Sim7			
SPIV[2]	 (Ref 2)	 (Ref 2)	

<table>
<tr><th colspan="2">Approximate Size and Location of Vortex Cores</th></tr>
<tr><td colspan="2">From the 2D data collected, the vortex cores were approximated to be ellipses, and size and location were found and plotted for 4″, 8″, 12″, 16″ downstream of TE.</td></tr>
<tr><td></td><td>Legend</td></tr>
<tr><td>
</td><td>Purple = 4″ downstream
Blue = 8″ downstream
Green = 12″ downstream
Red = 16″ downstream</td></tr>
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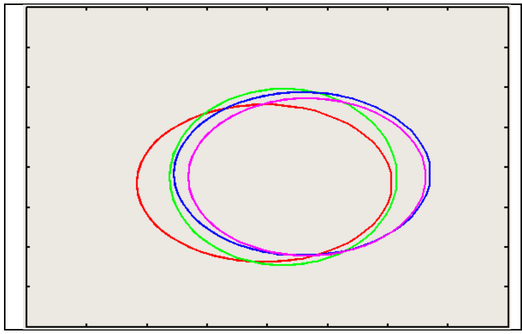

Discussion

<u>Instantaneous Velocity over Freestream Velocity with Equivalent SPIV Images</u>

- All three simulations and SPIV show a counterclockwise “curl” forming downstream of the right edge of the wing and from the color scale confirms an expected inverse relationship between vortex velocity and distance from the center (Ref 1).
- The shapes of Sim3 and Sim7 more closely resemble that of SPIV for both downstream locations.
- Sim7 shows more detail than Sim3 and is most like the SPIV plots, as at the 16” mark the plot clearly shows a defined vortex core separated from the horizontal “wash” of the wing.

<u>Vortex Core Size and Location Approximation</u>

As downstream distance from the trailing edge increases:

- Sim0 only shows increase in vortex core area with no core displacement
- Sim3 shows increasing change in area and a core displacement up and to the left.
- Sim7 shows a change in area and a core displacement that approximately follows a concave down parabolic trajectory from right to left which, while exaggerated, resembles what is seen in the SPIV approximation.

Conclusion

- Simulated wingtip vortex development and behavior more closely resembles that of SPIV for finer and denser mesh sizes. The same can be said for vortex core area, and thus the size of the vortices can be approximated by future simulations using a mesh size at least that of Sim7.
- Future work for the simulations need more accurately measured dimensions and coordinates of vortices in the 2D plane, as well as have more exact data from the SPIV experiments. With more accurate measurements there is a need to numerically verify the error of the simulations in comparison to SPIV data to make a better judgment about whether the simulations are reliable to use.
- If the simulations for wingtip vortices are reliable, they can be used to make more efficient use of wind tunnel tests and aid in the design process of aircraft.

Acknowledgements

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References

Ref 1: Abbott, I. H., & von Doenoff, A. E. (1959). *Theory of Wing Sections - Including a Summary of Airfoil Data.* Mineola: Dover Publications, Inc.

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STEPHEN BECHTEL FUND

NASA

Simulation of Wingtip Vortices

Ryan Termath, Science and Teacher Researcher (STAR) Program, Cal Poly San Luis Obispo
Jason Lechniak, Keerti Bhamidipati, Air Force Flight Test Center, Edwards Air Force Base, CA

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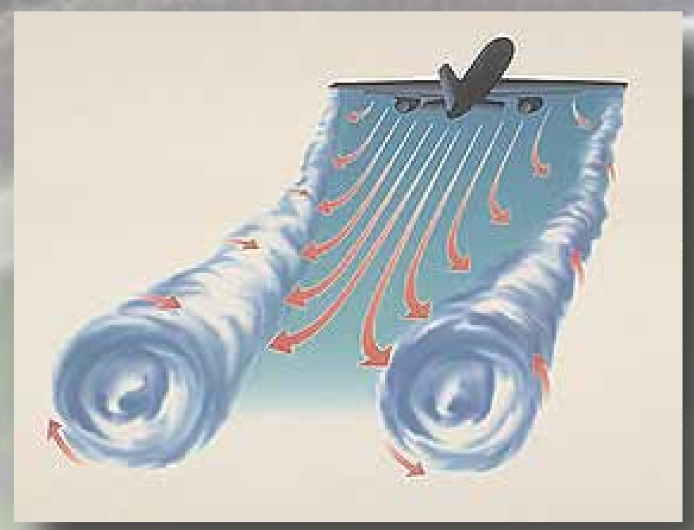
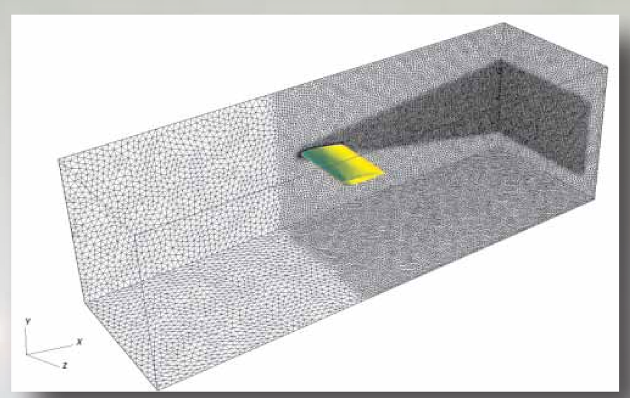
Computationally, modeling wing tip vortices has been a challenging area of study. It has only been in recent years that computational tools that better resolve and approximate wing tip vortices have been developed. This project sought to expand on gains by using incrementally more computationally intensive simulations. Determination of the accuracy of the modeled wing tip vortices was accomplished by comparing simulation results to experimental data.



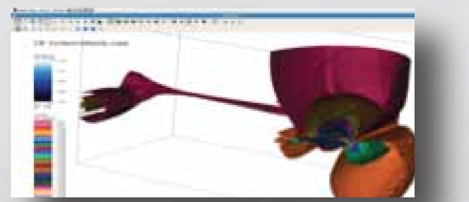
Visual Representation of Wingtip Vortices (Ref 3)

Part 1: Computer Simulation

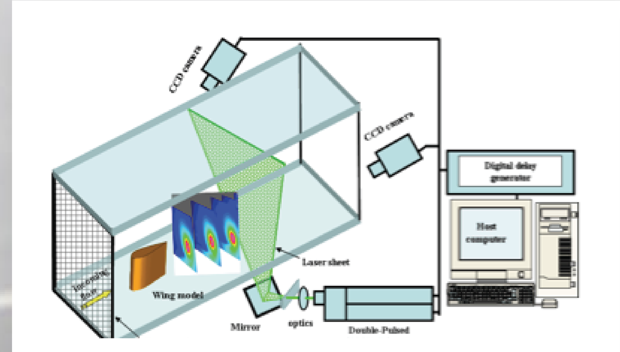


Example 3D mesh used in computer simulation

Numerical results of simulations sent to visualization program *VisIt*

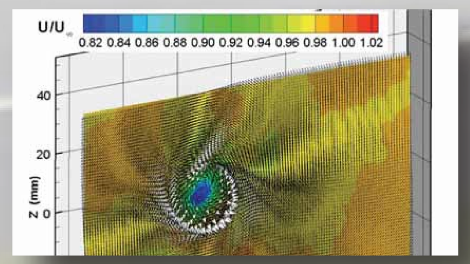


Part 2: Wind Tunnel Data



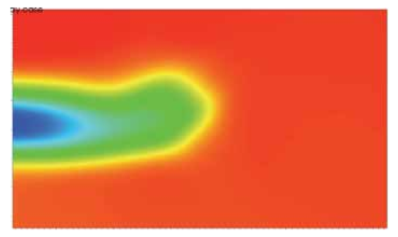
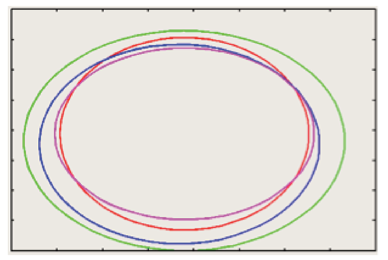
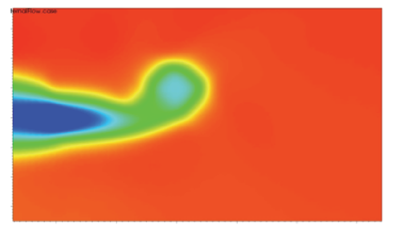
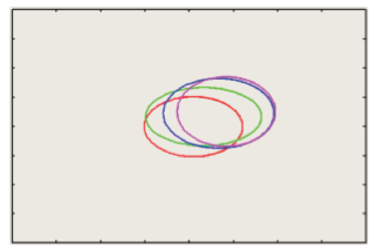
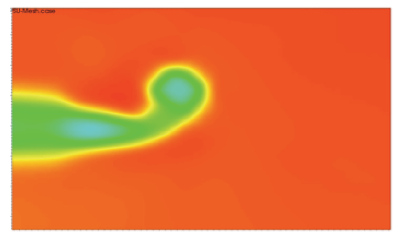
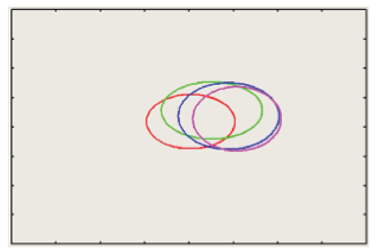
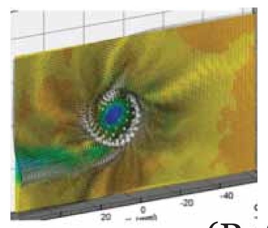
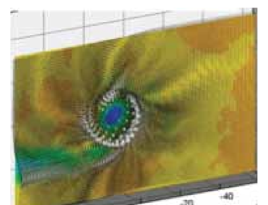
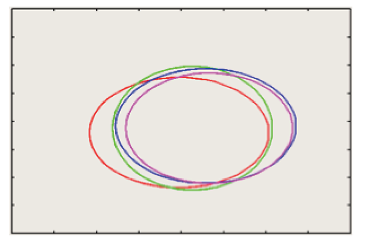
Experimental Setup using StereoScopic Particle Image Velocimetry (SPIV) (Ref 2)

Data from Iowa State University wind tunnel experiment compared to simulation



(Ref 2)

Results

Instantaneous Velocity over Freestream Velocity (U/U_∞) and Equivalent SPIV Images			Approximate Size and Location of Vortex Cores
Simulation	4" downstream of trailing edge	16" downstream of trailing edge	
Sim0			
Sim3			
Sim7			
SPIV	 (Ref. 2)	 (Ref. 2)	

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Vortex Core Size and Location Approximation

As downstream distance from the trailing edge increases:

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- Sim7 shows a change in area and a core displacement that approximately follows a concave down parabolic trajectory from right to left which, while exaggerated, resembles what is seen in the SPIV approximation.

Conclusion

a. Simulated wing tip development, behavior and core area more closely resemble that of the SPIV data for denser meshes. The physical size of vortex cores can thus be approximated by future simulations using a mesh size at least that of Sim7.

- Future work for the simulation need more accurately measured dimensions and coordinates of vortices in the 2D plane, as well as have more exact data from the SPIV experiments. With more accurate dimensions there is a need to numerically verify the error of the simulations in comparison to SPIV data to make a better judgment about whether the simulations are reliable to use.
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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the S.D. Bechtel, Jr. Foundation or the National Science Foundation.

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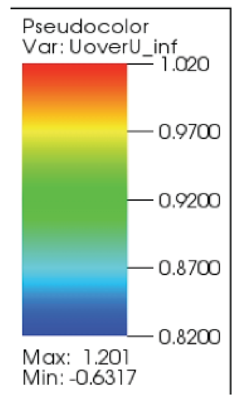
Legends

U/U_∞	Vortex Cores
	Purple = 4" downstream Blue = 8" downstream Green = 12" downstream Red = 16" downstream

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